

STRUCTURE, PROCESSING AND PROPERTIES OF POTATOES

**Isabel K. Lloyd
Kimberly R. Kolos
Edmond C. Menegaux
Huy Luo
Richard H. McCuen
Thomas M. Regan**

Materials and Nuclear Engineering Unit
University of Maryland
College Park, Maryland 20742-2115

Telephone 301-405-5221

Structure, Processing and Properties of Potatoes*

Isabel K. Lloyd, Kimberly R. Kolos, Edmond C. Menegaux, Huy Luo,
Richard H. McCuen and Thomas M. Regan
University of Maryland, College Park, MD

KEYWORDS: thermodynamics, structure, properties, processing, phase change

PREREQUISITE KNOWLEDGE: This material is intended for high school students in an engineering or materials science course or college freshman

OBJECTIVES:

General: To demonstrate the relation between processing, structure, and thermodynamic and physical properties.

Specific:

1. To show the effect of structure and structural changes on thermodynamic properties (specific heat) and physical properties (compressive strength).
2. To illustrate the first law of thermodynamics.
3. To compare boiling a potato in water with cooking it in a microwave in terms of the rate of structural change and the energy consumed to "process" the potato.
4. To demonstrate compression testing.

EQUIPMENT AND SUPPLIES:

19 Idaho potatoes (large) ¹	potato peeler	paring knife
voltage meter (to measure at least 120 V)	butcher knife	tongs
clamp on ammeter (0-15 amps)	oven mitts	1000 ml beaker
three wire extension cord	calipers	3 500 ml beakers
standard home microwave oven	300 ml ice	1 150 ml beaker
1.27 cm (1.2 in.) diameter wooden dowel	metal grinder	30.48 cm ruler
4 styrofoam cups (8 or 12 oz)	three wire extension cord	
digital scale (at least 1 kg capacity)	thermometer (-10°C-150°C)	
2 5.08 cm (2 in.) C clamps	laboratory weights (~50 kg total)	
a bucket or very large beaker		

* Support for the development of this experiment was provided by the National Science Foundation via the ECSEL Coalition.

¹ 3 potatoes for each boiling or microwave test time and 1 for the specific heat tests.

type T (copper-constantan) thermocouple and a digital readout or low mass thermometer (0-150°C)
hot plate (variac type power supply, so that power is continuously supplied)
stainless steel pipe: ID=3.175 cm (1 1/4 in.), OD=4.123 cm (1 5/8 in.), length= 25.4 cm (10 in.)
miter box, fit to cut a 3.05 cm (1.2 in.) diameter potato specimen
Lugol's Iodine: 0.2 % iodine and 0.4 % potassium iodide in water
compression tester (See appendix A for instructions for the compression tester. The general form, not the exact size, of the tester is important.)

INTRODUCTION:

In this experiment, potatoes will be "processed" by cooking cylindrical specimens in both boiling water and the microwave. During the cooking processes, potatoes undergo structural changes that affect their properties. The specific heat of a potato is similar in both the raw and fully cooked state. However, it increases dramatically as the potato undergoes the phase change which occurs to yield the state we regard as cooked. The compressive strength of the potato changes significantly as the potato is cooked; the change in the strength of a potato due to processing will be monitored by performing a compression test on samples cooked for different lengths of time. The changes in the cells and cell walls will be observed by staining the potato specimens with a solution of potassium iodide, and the change in the composition of the potatoes will be observed by noting the difference in the mass of the specimens before and after cooking.

What is the chemical composition of a potato?

Raw potatoes consist largely of starch (~17 weight %) and water (~80 weight %). Starch is a natural high polymer of glucose. The main starches in potatoes are amylose (which has an average molecular weight of ~100,000) and amylopectin (which has an average molecular weight of ~1,000,000). The chemical composition of potatoes varies depending upon the variety and age, as well as how a potato is grown, stored, and processed (Talbert and Smith, 1959, as indicated by Mohsenin, 1986, p.445). Because of this variance, the tests conducted herein will be made with the same type of potato, preferably bought at the store at the same time. The potatoes will be peeled, cut into specimens, and soaked in water. To avoid bias during the testing, samples for each test should be taken from several different potatoes.

What happens to a potato when it is cooked?

The important change that takes place when a potato is cooked is the change of starch granules from a group of hard, compacted starch molecules to a tender, swollen mass. When they begin to take in water, the granules swell and "gelatinize". Gelatinization is a complex process. It involves the melting of the starch molecules within the cells as well as their hydration and dissolution

(Lelièvre). A chemically bonded structure similar to that of gelatin (JELLO™) or cement is formed during the process. Since the starch molecules have a variety of molecular weights and since processes other than melting are occurring, gelatinization in a potato occurs over a range of temperatures (roughly 58°C to 66°C or 137°F to 150°F (McGee, p. 175)) rather than at a single temperature like the melting of water. During this phase change the specific heat increases dramatically. When the cell walls rupture during cooking, the gelatinized starch is released, which is evident from the stickiness of a cooked potato. The starch gelatinization and the rupture of the potato-cell walls decreases the compressive strength of potatoes.

How does a microwave work?

The microwaves produced in a microwave oven create an electromagnetic field. Polar molecules in this field tend to align their dipole moment with the direction of the field. The frequencies used in microwaves provide a field that changes at about the same rate as it takes a water molecule to align in the field (Walker, p. 134). Since the field is continuously reversing with a frequency in the range of 1×10^9 to 5×10^{12} Hz (Walker, p. 134), the water molecules are constantly rotating, bumping into each other, and generating heat due to friction. Since potatoes consist of approximately 80% water, they cook well in the microwave.

What is the First Law of Thermodynamics?

Materials Scientists state the First Law of Thermodynamics as: Whenever a system undergoes a change in state, the change in the internal energy of the system is equal to the heat input to the system minus the work output by the system ($dU = \delta q - \delta w$). Other engineers tend to state it as: During a cycle that a system undergoes, the cyclic integral of the heat is proportional to the cyclic integral of the work. In simpler terms, the First Law states that energy is conserved.

What is specific heat?

The specific heat or heat capacity of a system is the ratio of the heat added or withdrawn from the system to the resultant change in temperature of the system. At constant pressure, $C_p = (\delta q / \delta T)_p$. We can also relate the specific heat to the internal energy and enthalpy of the system, $C_p = (\delta U / \delta T)_p = (dH / dT)_p$. The specific heat of water is 4.190 kJ/kg. The average specific heat of potatoes is 3.39 kJ/kg (Hayes, p. 65).

How will the compressive strength be characterized?

A compression tester will be used to develop a stress-strain curve for potatoes. The tester consists of a piston that moves through a rigid support. The specimen is placed beneath the piston, and weights are applied to the top of the piston. The change in the height of the specimen will be an indication of the strain induced by the force of the weight. The equations that will be used are:

$$\text{compressive stress} = F / A_0 \quad (1)$$

$$\text{strain} = (l_i - l_0) / l_0 \quad (2)$$

where F is the force applied by the weight, A_0 is the original area of the specimen, l_0 is the original length of the specimen and l_i is the length of the specimen after applying force F . The average strain will be found by testing three specimens at each cooking time. The test will be performed by applying stress to a specimen until it fails or until the required weight exceeds the available weight.

PROCEDURE:

Preparation: Potato corer

Sharpen one end of the stainless steel pipe by grinding the edge to a thickness of about 1 mm. Be careful to keep the circular shape of the pipe.

Preparation: Potato specimens

1. Peel and then rinse one potato. Using the butcher knife dice it into cubes which are roughly 2 mm on a side. This should yield enough potato to do the specific heat measurements.
2. Peel three Idaho potatoes (three potatoes should yield enough specimens to perform three compression tests, compute the mass difference after cooking, and observe structural changes by staining). Soak the peeled potatoes in a bucket of water while peeling the others to prevent discoloration due to contact with the air.
3. Cut into a potato using the potato corer to get a cylindrical piece of potato in the pipe at least 2.5 cm (0.984 in.) long (see Fig 1).
4. Using the wooden dowel, push the specimen back out the pipe until a straight-cut can be made on the bottom of the potato cylinder; cut the bottom with the edge of the knife blade against the pipe. Use the wooden dowel to push the remainder of the specimen out of the pipe.
5. Repeat steps 3 and 4 to obtain three additional 2-cm specimens.
6. Using the miter box to keep the ends straight, cut four specimens, each with a length of 2 cm (0.787 in.); they will be tested in the compression tester.
7. Cut a 2-mm thick half-circle off of the top of the fourth 2-cm specimen (see Fig. 2); this specimen will be used to observe mass and temperature changes.
8. Cut another cylinder to a length of 4 cm (1.575 in.); this specimen will be used to show the extent of cooking through staining.
9. Place the five specimens in a 500-ml beaker. Fill the beaker with water so the potatoes are covered.

Preparation: Initial compression tester measurements

1. Weigh the piston and top plate; record the total mass on the worksheet. *(Remember to add this mass to the masses placed on top of the piston.)*

2. Determine the datum points on both the left-hand and right-hand rulers (see Fig. 3).

Testing: Specific heat measurements

Safety note: Use an oven mitt to handle the beaker of hot water.

Note: If a low mass thermometer is used to measure temperatures instead of a thermocouple, take care not to puncture the styrofoam cups.

1. Record the weight of 2 nested styrofoam cups (these act as your calorimeter) on the worksheet.
2. Add approximately 30 g of the finely diced raw potatoes to the cups and record the total weight on the worksheet.
3. Measure the temperature of the potatoes and record it on the worksheet.
4. In a 150 ml beaker heat about 100 ml of water in the microwave for 20 sec. at full power.
5. Measure the temperature of the heated water and then immediately pour the water into the styrofoam cup calorimeter with the potatoes. Stir the water and potatoes with the thermocouple or the low mass thermometer. As soon as the temperature stabilizes, record it on the worksheet.
6. Weigh the calorimeter, potatoes and water; record the value.
7. Carefully pour the water down the drain and throw the potatoes away. Dry the styrofoam cups.
8. Repeat the above using 100 ml of water heated in the microwave for 30 sec., 1 min. and 1 min. 30 sec. Fresh minced potato should be used for each test.
9. Record the weight of the other 2 nested styrofoam cups on the worksheet.
10. Add approximately 30 g of the finely diced potatoes to the cups and record the total weight.
11. Microwave the "calorimeter" with the raw minced potatoes for 2 min. 15 sec. Then remove it from the microwave using the oven mitt.
12. In a 150 ml beaker heat about 100 ml of water in the microwave for 1 min. 45 sec. at full power.
13. Measure and record the temperature of the cooked potatoes.
14. Repeat steps 5-7. (Be sure to stir the potatoes to break them apart.)
15. Repeat steps 10-14 using water heated in the microwave for 2 min. Use fresh minced potatoes for the new test.

Testing: Boiling potatoes

1. Fill a 1000-ml beaker with 400 ml of water, measure and record its temperature and place it on the hot plate. Record the time at which you place the beaker on the hot plate.

2. Measure and record the input voltage from the outlet where the hot plate is plugged in. Measure and record the amount of current flowing to the hot plate. An old extension cord with the outer insulation cut away at one section may be used to measure the input current with the clamp on ammeter since the clamp on meter should only be placed around one wire.

Safety note: Only the outer insulation should be cut away on the extension cord - no bare wires should be exposed. Check with an electrician or the electrical shop teacher.

3. From the 500-ml beaker remove the specimen with the half circle cut from the top (this will be referred to as the notched sample), shake off the excess water, and record the mass of the specimen. Then shake off the excess water from the other four specimens and record the total mass of the specimens.
4. Record the temperature of the water in the beaker where the potatoes are stored.
5. When the water on the hot plate reaches 100°C, record the time. Then, put the five potato specimens in the water (including both the notched specimen and the longer specimen for staining) and record the starting time.
6. Cook the potatoes for a specified time. It is recommended that the experiment be performed for at least three time intervals: 2 1/2 minutes, 6 minutes, and 12 minutes are suggested. For each time interval, five new potato specimens must be used.
7. At the end of the cooking time-interval, immediately remove the potatoes with the tongs; immediately immerse the long specimen in a 500-ml beaker of ice water.
8. Shake the excess water from the notched specimen and quickly record the mass of the marked specimen by recording the first stable mass reading; it is recommended that a balance with a digital scale be used because the mass of the specimen will continue to change. Once the mass is recorded, measure the surface temperature of the potato; use the highest temperature the thermometer reaches while it is resting on the top of the potato against the uncut semicircle (see Fig. 2).
9. Measure the volume of water remaining in the 1000 ml beaker after the potatoes have been boiled. Record it on the worksheet.
10. Let the potatoes (except the long specimen in ice water), cool in air for 10 minutes and again record the mass and temperature of the notched specimen.
11. Perform the staining and compressive strength tests on the appropriate specimens.

Testing: Microwave cooking

1. Determine the amount of time required to cook the potatoes.
 - a. Fill a 500-ml beaker with 300 ml of water and place it in the microwave.
 - b. Measure the voltage at the outlet with the volt meter. Then use the extension cord to plug in the microwave and use the clamp on ammeter to measure the current. Turn the microwave on for 1 minute and record the input current and voltage.
 - c. Calculate the power input to the microwave by multiplying the input current by the input voltage.
 - d. Calculate the energy input from the hot-plate by multiplying the cooking time by the power input. Divide the calculated hot plate energy input by the power input to the microwave to determine the cooking time period required for comparable input energy.

Example:

microwave: current = 9.5 A; voltage = 117.3 V
 power input = $9.5 \times 117.3 = 1114$ W
hot plate: current = 1.8 A; voltage = 118.6 V
 power input = $1.8 \times 118.6 = 213.5$ W
 energy input = $213.5 \text{ W} \times 720 \text{ s} = 153.7 \text{ kJ}$
microwave cooking time = $153.7 \text{ kJ} / 1.114 \text{ KW} = 138 \text{ s}$

- e. Choose three microwave cooking times. Use one time period for which the boiling time and the microwaving time are approximately equal. (For a microwave rated 700 W or higher energy microwave, appropriate times are roughly 0.5, 1 and 2.5 min.)
2. On a sheet of paper, draw five lines 7 cm (2.75 in.) long, at 72° angles (See Fig . 4). At the end of each line, draw a circle approximately the same size as the potato specimens. Label the circles according to Fig 4, where mass is the spot for the half- circle notched specimen, stain is for the long specimen, and the numbers are for the specimens to be tested in the compression tester.
3. Remove the notched specimen from the 500-ml beaker, shake off the excess water, and record the mass of the specimen on a fresh copy of pages 2 and 3 of the worksheet. Then shake off the excess water from the other four specimens and record the total mass of the specimens.
4. Record the temperature of the water in the beaker where the potatoes are stored.
5. Place the potato samples in the microwave on the sheet of paper with the specimens standing up.
6. Cook a set of potatoes for each of the chosen time periods; be sure to measure and record the input voltage from the outlet where the microwave

is plugged in and measure the amount of current flowing to the microwave for each cooking time.

7. Remove the potatoes with the tongs and immediately immerse the long specimen in a 500-ml beaker of ice water.
8. Quickly record the mass of the notched specimen by recording the first stable mass reading; it is recommended that a balance with a digital scale be used because the mass of the specimen will continue to change. Once the mass is recorded, measure the surface temperature of the potato; use the highest temperature the thermometer reaches while it is resting on the top of the potato against the uncut semicircle (see Fig. 2).
9. Let the potatoes (except the long specimen in ice water), cool in air for 10 minutes and again record the mass and temperature of the marked specimen.
10. Perform the staining and compressive strength tests on the appropriate specimens.

Testing: Staining

1. Remove the cooked potato from the ice water.
2. Cut through the center of the specimen, leaving two small cylinders.
3. Rinse the freshly cut ends of the cylinders in the water to remove any starch molecules that were knocked loose by the knife.
4. Cover the cut ends with the potassium iodide solution and note the shape and color of the staining.

Testing: Compressive strength (Requires a group of at least two)

Clamp the compression tester to a table using the two C clamps.

Responsibilities:

Student A:

Measure initial diameter of each specimen

Determine base-level elevations on both left-hand ruler and right-hand ruler (see Fig. 3)

Measure top-plate elevations (see Fig. 3)

Student B:

Add masses to weight stand

Ensure masses are centered and stable

Record all data on worksheet

Both A & B:

Initially align (center) piston and top plate over specimen.

1. Student A should measure and record the initial diameter of the specimen.

2. Set the potato specimen under the hole in the compression tester and center the small plate on top of the potato specimen. Insert the piston and center it over the specimen; let it rest on the small plate. Record the left-hand and right-hand top-plate elevations of the potato specimen as read directly from the rulers; these values will be used to calculate the initial length of the specimen.
3. Student B should successively place masses on the piston and record the masses. Student A should immediately state the resulting top-plate elevations with Student B recording the elevations on the worksheet. Use the following chart as a guide to the amount of mass to use for various cooking times:

Cooking Method	Cooking Time (Min)	Mass Increment (kg)	Maximum Load (kg)
Microwave	less than 1	4	36
	1 or more	1	16
Boiled	less than 6	4	36
	6 or more	1	16

4. Student B should continue to add weight to the piston until the specimen fails or until the maximum load of allowable mass has been reached. For safety reasons, Student B should make sure that the masses are centered and the pile of masses is stable.

Post-lab questions:

1. Complete all computations on the worksheet.
2. Plot the specific heat of the potatoes against the final temperature.
3. Calculate the average value of the specific heat for tests where the potato was above and below the gelatinization range. How does this value compare with the specific heat of water? Do you think that this is a meaningful comparison? Why?
4. Why is there such a large increase in specific heat during gelatinization?
5. Why did the mass of the cooked potatoes decrease after the potatoes cooled?
6. How is heat imparted to the potatoes when they are boiled in water?
7. Combine the stress-strain data for the three specimens cooked at the same temperature, and use a curve-fitting program to fit the data to a power model ($Y = aX^b$ where Y is the stress and X is the strain). Plot the data and the corresponding function.

8. Graphically compare the following:
 - a. Stress-strain curves for the potatoes cooked in the microwave at different times.
 - b. Stress-strain curves for the potatoes cooked in boiling water at different times.
 - c. Stress-strain curves for the microwaved and boiled potatoes cooked with the same input energy.
 - d. Stress-strain curves for the microwaved and boiled potatoes cooked for the same time.
9. Discuss the energy efficiency you obtained for microwave cooking. How would you account for the remaining energy?
10. Discuss the energy efficiency you obtained for boiling the potatoes in water. How would you account for the remaining energy? What role does time play when you are considering a cooking method?
11. Which is more energy efficient, microwaving or boiling? If you didn't consider the time it took to boil the water, how would the efficiencies compare? Would your answer change if you added in the energy efficiency in the process required to produce the input energy? Would your answer change if you considered the time that consumers typically used to cook potatoes?
12. What type of values for the voltage and current did your meters measure, rms (root mean square), average, peak or peak to peak? What is the most appropriate value to measure? How would the measurement errors in your energy measurements affect the energy efficiency calculations?

Potato Worksheet

A. Specific Heat Tests

	Raw Potato; 20 sec. water	Raw Potato; 30 sec. water	Raw Potato; 1 min. water	Raw Potato; 1 min 30 sec. water	Cooked Potato; 1 min. 45 sec. water	Cooked Potato; 2 min. water
mass cups (g)						
mass cups and potatoes (g)						
mass potatoes (g)						
mass cups, pot. and water (g)						
mass hot water (g)						
T _{potatoes} (°C)						
T _{hot water} (°C)						
T _{final} (°C)						
specific heat pot. (J/kg).						

The specific heat of the potatoes is calculated using the formula:

$$c_{\text{potatoes}} = \frac{-m_{\text{hot water}} \cdot c_{\text{water}} \cdot (T_{\text{final}} - T_{\text{hot water}})}{m_{\text{potato}} \cdot (T_{\text{final}} - T_{\text{potato}})}$$

(The specific heat of water is 4190 J/kg°C.)

Cooking process: _____	Time cooked: _____
Time for water to boil: _____	Input voltage: _____
Total mass of 5 samples: _____	Input current: _____
Mass of notched sample before cooking: _____	Surface temperature before cooking: _____
Mass of notched sample after cooking (hot): _____	Surface temperature (hot) after cooking: _____
Mass of notched sample after cooking (cool): _____	Surface temperature (cool) after cooking: _____
Volume of water which evaporated during boiling: _____	Right datum point: _____
Mass of piston and top plate: _____	Left datum point: _____

342

Mass differences for the notched sample:

Mass loss (hot) = Mass before cooking - Mass after cooking = _____

% Mass loss (hot) = (Mass loss / Mass before cooking) X 100% = _____

Mass loss (cool) = Mass before cooking - Mass after cooking = _____

% Mass loss (cool) = (Mass loss / Mass before cooking) X 100% = _____

Staining observations:

Record any observations made during the staining process. If a regular geometric shape was observed, record the dimensions.

Stress-strain calculations:

Make a chart with the following columns:

Mass, Applied force, STRESS, true height (left), true height (right), average height, STRAIN.

Use the following equations to calculate the stress applied to the potato and corresponding strain:

STRESS: Original area of the specimen (m^2) = $A_0 = \pi d^2 / 4$
Applied force (kN) = Mass (kg) X 9.81 m/sec^2 X 1000
STRESS (kPa) = Applied force / Original area

STRAIN: True height (left) = Measured height (left) - Left datum point
True height (right) = Measured height (right) - Right datum point
Average height = [True height (left) + True height (right)] / 2
STRAIN = (average height - original height) / original height

Energy calculations:

Input power = Input current * Input voltage = _____ W

Input energy = (Input power * Cooking time in seconds) / 1000 = _____ kJ

The First Law of Thermodynamics states that energy is conserved. Therefore, all of the energy we put into the system can be accounted for directly or as waste heat. The ratio of the energy we need with the energy we use is the efficiency.

1. Microwave cooking:

Theoretically, microwave cooking should be very efficient since microwaves are designed to heat up the food rather than the cooking medium. Therefore, the minimum energy required to cook a potato is the energy required to heat the potato to the final temperature, E_1 , and the energy required for gelatinization, E_2 .

- a. Look at your compression test data and determine the minimum cooking time required to fully cook the potatoes in the microwave. Use the data from that test to estimate the minimum cooking energy and the energy efficiency.
- b. Calculate the minimum energy, E , required to cook the potatoes:

$$E = E_1 + E_2 = \underline{\hspace{2cm}}$$

$$E_1 = \text{mass potatoes cooked} * \int_{T_i(^{\circ}\text{C})}^{T_f(^{\circ}\text{C})} c_{\text{potato}} dT = \underline{\hspace{2cm}}$$

E_2 = Enthalpy or heat of gelatinization. Since the enthalpy of gelatinization is not available, we will roughly estimate it by the latent heat of potatoes which is 258 kJ/kg.

$$E_2 = \text{mass of potatoes cooked} * 258 \text{ kJ/kg} = \underline{\hspace{2cm}}$$

- c. Calculate the efficiency of the microwave cooking process for your samples.

$$\text{efficiency} = e = \text{minimum energy required} / \text{energy input} = \underline{\hspace{2cm}}$$

2. Boiling in water:

- a. Look at your compression test data and determine the minimum cooking time required to fully cook the potatoes by boiling. Use the data from that test to estimate the minimum cooking energy and the energy efficiency. (Note: you must include the time it took to boil the water for a fair comparison with microwave cooking):

- b. Calculate the minimum energy, E , required to cook the potatoes by boiling. Since you must boil the water as well as cook the potatoes, you will need to add two more terms, E_3 and E_4 , to E . E_3 is the energy to raise the temperature of the water from the initial temperature to 100°C . E_4 is the heat of vaporization used by the water which evaporates during the boiling process.

$$E = E_1 + E_2 + E_3 + E_4 = \text{-----}$$

$$E_1 = \text{mass potatoes cooked} * \int_{i=T_i(^{\circ}\text{C})}^{T_f(^{\circ}\text{C})} c_{\text{potato}} dT = \text{-----}$$

$$E_2 = \text{mass of potatoes cooked} * 258 \text{ kJ/kg} = \text{-----}$$

$$E_3 = \text{mass water boiled} * \int_{i=T_i(^{\circ}\text{C})}^{T_f(^{\circ}\text{C})} c_{\text{water}} dT = \text{-----}$$

(The heat capacity of water is $4190 \text{ J/kg}\cdot^{\circ}\text{C}$.)

$$E_4 = \text{heat of vaporization of water} \\ = \text{mass water evaporated} * 2254 \text{ J/kg} = \text{-----}$$

- c. Calculate the efficiency of the boiling of your samples.

$$\text{efficiency} = e = \text{minimum energy required} / \text{energy input} = \text{-----}$$

INSTRUCTOR NOTES:

Appendix B contains curves with sample data for all of the experiments. Fresh copies of pages 2 and 3 of the worksheet are required for each boiling and microwaving test.

REFERENCES:

Haytowitz, D. B. and Matthew, R. H., *Compositions of Foods: Vegetables and Vegetable Products*, *Agriculture Handbook 8-11*, 294-297, USDA, Washington D.C., 1984.

Hayes, G. D., *Food Engineering Data Handbook*, John Wiley and Sons, New York, 1987.

Hunt, R. G., "The Physics of Popping Popcorn," *The Physics Teacher*, **29**, 230-235 (1991).

Lelièvre, J., "Gelatinization of Crosslinked Potato Starch," *Starch/Starke* 37, 267-269 (1985).

McGee, H., *On Food and Cooking*, Macmillan Publ. Co., New York, 1984.

Mohsenin, N.N., *Electromagnetic Radiation Properties of Foods and Agricultural Products*, Gordon and Breach Science Publishers, New York, 1984.

Mohsenin, N. N., *Physical Properties of Plant and Animal Materials*, Gordon and Breach Science Publishers, New York, 1986.

Pomeranz, Y., *Food Analysis: Theory and Practice*, Van Nostrand Reinhold Co., New York, 1987.

Talburt, W.F. and Smith O., *Potato Processing*, AVI Publishing Co., Westport, Conn, 1959.

Walker, J., "The Amateur Scientist", *Sci. Amer.*, **256**, 134-138 (1987).

SOURCE OF SUPPLIES:

Most of the supplies are readily available in the typical high school chemistry or physics laboratory or the grocery store. The clamp on ammeter and voltmeter (a multimeter is fine) are available from an electrical supply house, including the Radio Shack catalog, the clamp on meter is ~\$50. The dowel, pipe, screws, etc. should be available from a home building supply store or the school shop. The metal necessary for the compression tester may be available in the school shop.

APPENDIX A THE COMPRESSION TESTER

SUPPLIES:

- 1 piece of metal (steel or aluminum) 91.44 cm x 5.08 cm x 0.635 cm (36 in. x 2 in. x 1/4 in.) to be cut into 3 equal pieces
- 2 - 1.588 cm (5/8 in.) bolts, 15.24 cm (6 in.) long
- 4 - 1.588 cm (5/8 in.) hex nuts
- 4 - 1.588 cm (5/8 in.) flat washers
- 1 - solid aluminum shaft, 2.54 cm (1 in.) diameter, 12.7 cm (5 in.) long with the ends squared
- 1 - aluminum plate, 10.16 cm x 6.35 cm x 1.27 cm (4 in. x 2 1/2 in. x 1/2 in.)
- 1 - 0.635 cm (1/4 in.) flat head screw, 2.54 cm (1 in.) long
- 2 - 15.24 cm (6 in.) rulers
- 1 - small circular plate, 5.08 cm (2 in.) diameter, 0.9525 cm (3/8 in.) thick (this is referred to as the top plate)
- 2 - 5.08 cm (2 in.) C clamps
- drill press with 5/8 in. drill bit, 1 in. drill bit, 1/4 in. drill and No. 7 drill

1/4-20 tap	center punch	counter sink
hacksaw	file	

Construction of the compression tester:

Warning: The compression tester should be built by a person with machine shop experience. Safety glasses should be worn throughout the process.

1. Cut the 91.44 cm (36 in.) piece of metal into three equal parts with the hacksaw.
2. File the sharp edges using a metal file.
3. Stack the three pieces of metal on top of one another and clamp the ends with the two C clamps.
4. Draw a line lengthwise through the center of the 30.48 cm (12 in.) piece. Draw three perpendicular lines at 5.08 cm (2 in.), 15.24 cm (6 in.) and 25.4 cm (10 in.) from one end of the piece.
5. Center punch a dimple at each of the three line intersections.
6. Drill a 1.588 cm (5/8 in.) hole through the clamped pieces at the 5.08 cm (2 in.) and 25.4 cm (10 in.) intersections.
7. Unclamp the three pieces and reclamp two of the pieces using the 1.588 cm (5/8 in.) bolts as locating pins through the two drilled 1.588 cm (5/8 in.) holes, keeping the marked piece on top.

8. Drill a 1.588 cm (5/8 in.) pilot hole through the clamped pieces at the 15.24 cm (6 in.) mark. Redrill the hole with the 2.54 cm (1 in.) drill bit. Unclamp the pieces.
9. Locate the center of the 2.54 cm (1 in.) solid shaft and dimple it with a center punch. Using a No. 7 drill, drill a 1.588 cm (5/8 in.) deep hole. Thread the hole using the 1/4-20 tap.
10. Locate the center of the 10.16 cm by 6.385 cm (4 in. by 2 in.) aluminum plate and dimple it with the center punch. Drill a 0.635 cm (1/4 in.) hole through the plate and counter-sink it deep enough to make the head of the 0.635 cm (1/4 in.) flat-head screw flush with the top of the plate.
11. Place the plate on top of the shaft, insert the 0.635 cm (1/4-in.) flat-head screw through the plate into the shaft, and tighten the screw.
12. Assemble the framework using Fig. 3 as a guide. Put the two 1.588 cm (5/8 in.) bolts through the 30.48 cm (12 in.) piece with only two holes and install one 1.588 cm (5/8 in.) nut on each bolt, leaving 9.525 cm (3 3/4 in.) between the nut and the head of the bolt. Install one of the remaining 30.48 cm (12 in.) pieces through the outside holes over the bolts and place two washers on each bolt. Place the remaining 30.48 cm (12 in.) piece on the bolts, lock the assembly together with one nut on each bolt, and tighten all four nuts. Insert the shaft with the attached plate through the 2.54 cm (1 in.) hole in the center of the framework.
13. Set the small circular plate underneath the shaft. Tape two 15.24 cm (6 in.) rulers to the framework in such a way that the centimeter markings on each ruler are at the outer edges of the circular top plate.

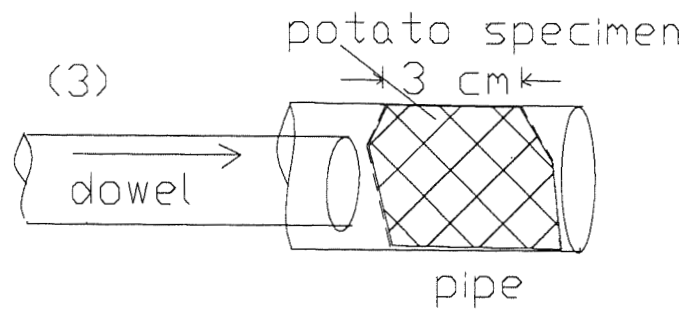
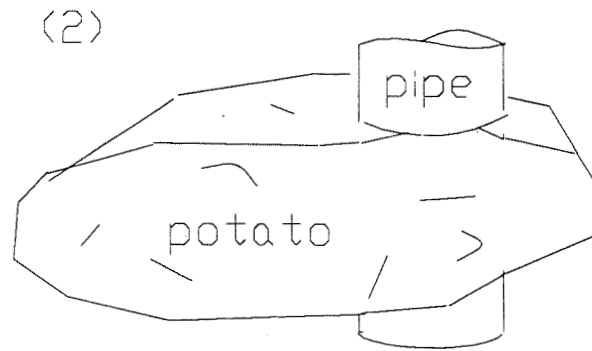
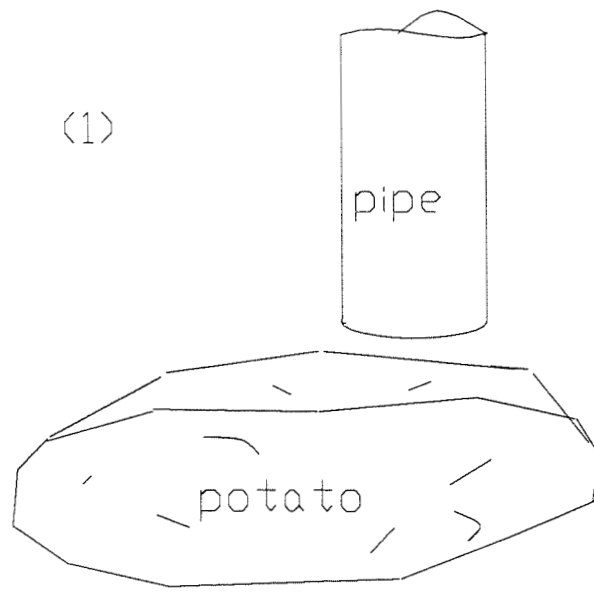
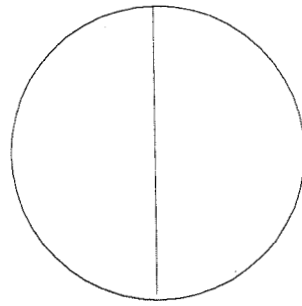
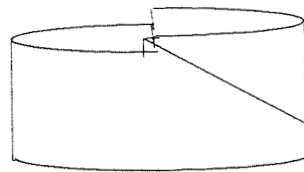


Figure 1. Preparing potato specimens using a sharpened pipe.

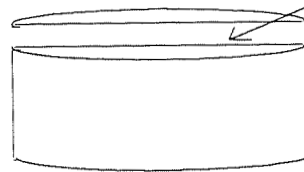
Top view



Side view



Front view



Placement of
thermometer

Figure 2. Views of the half circle cut on the potato specimen to be weighed and proper placement for the thermometer during temperature measurements.

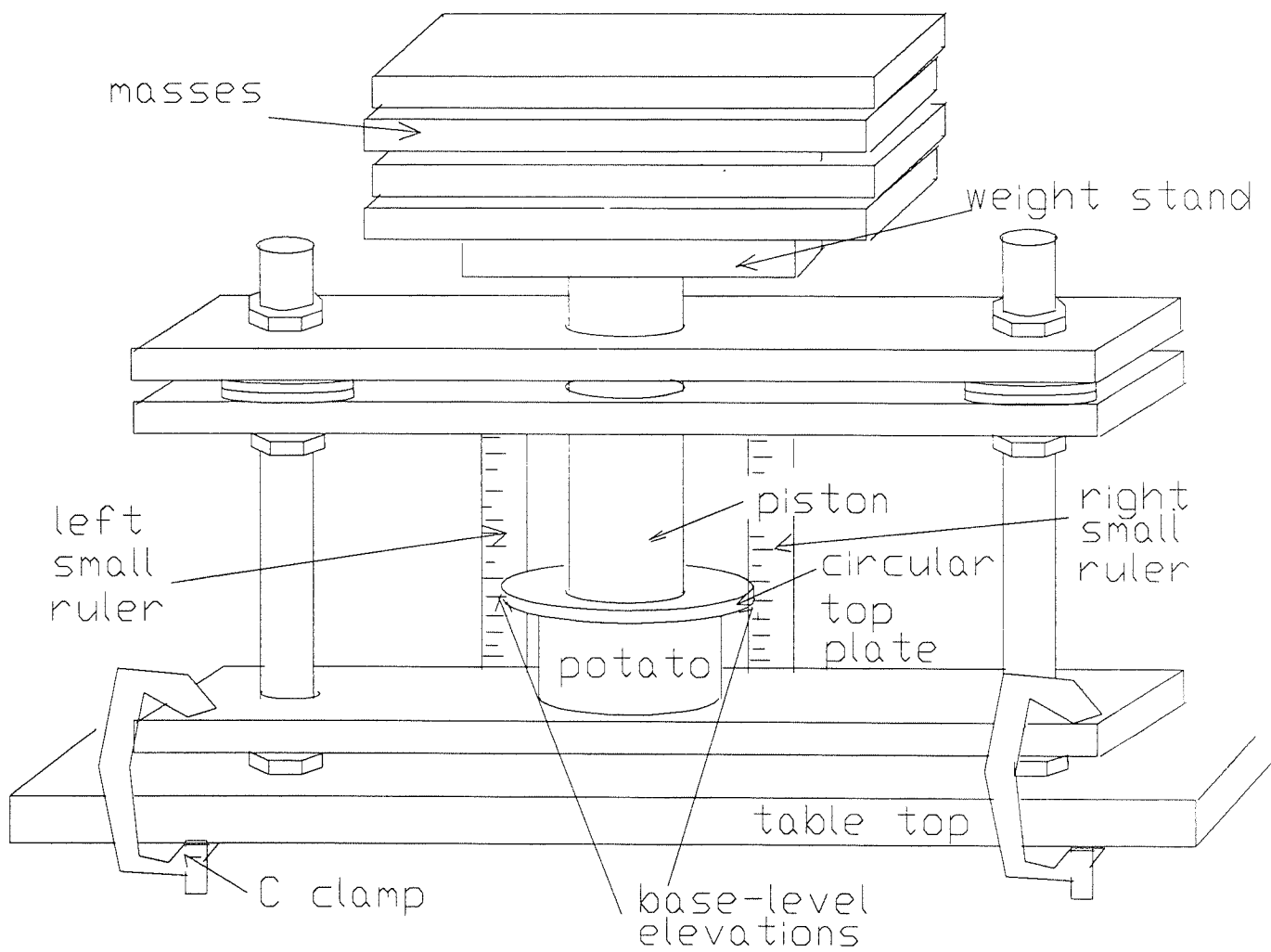


Figure 3. Compression tester used to test the compressive strength of potatoes.

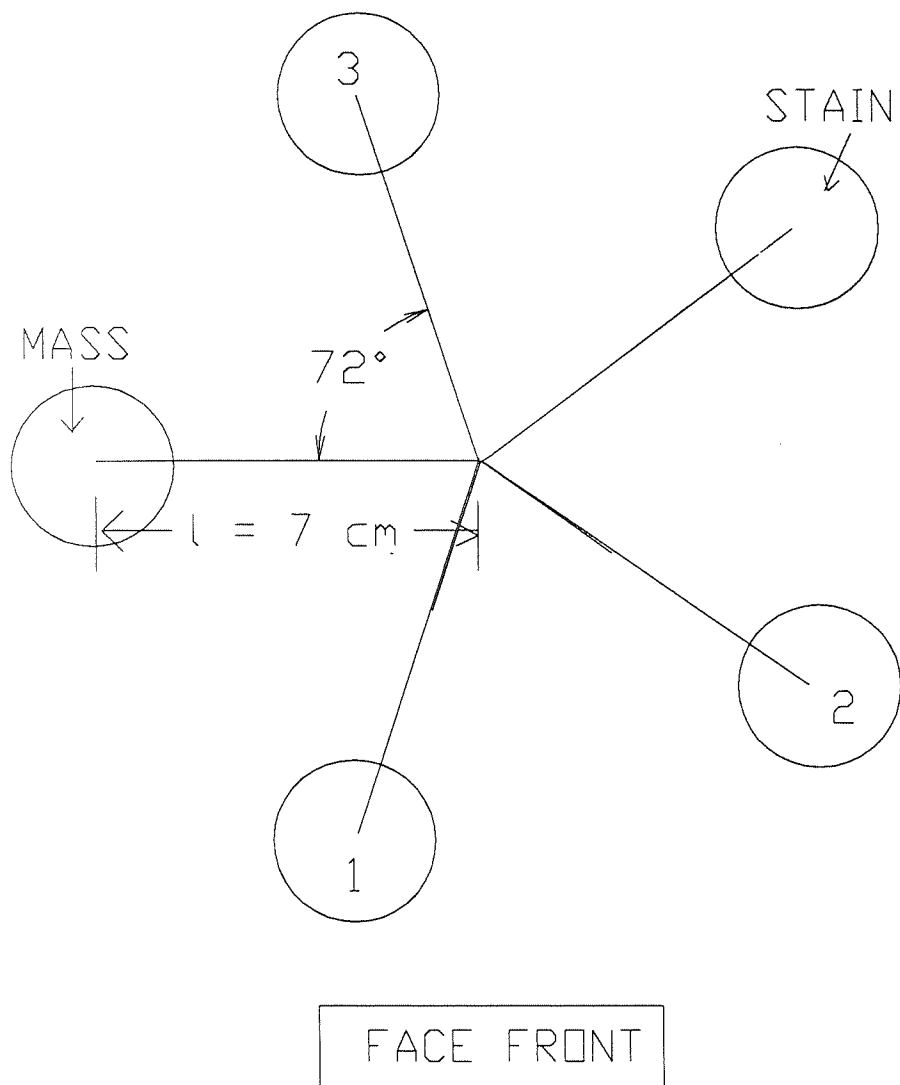


Figure 4. Diagram for making the sheet required for the proper placement of potato specimens in the microwave.

APPENDIX B SAMPLE DATA

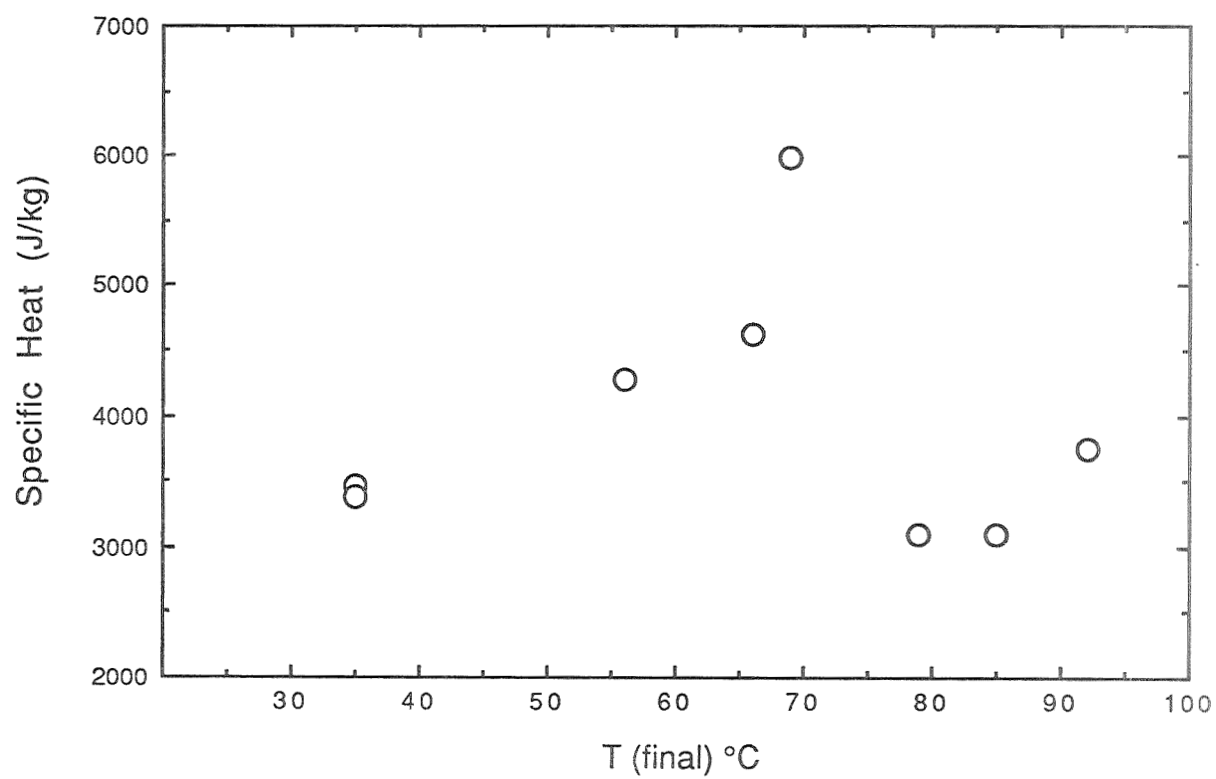


Figure B1: Specific heat versus the final temperature.

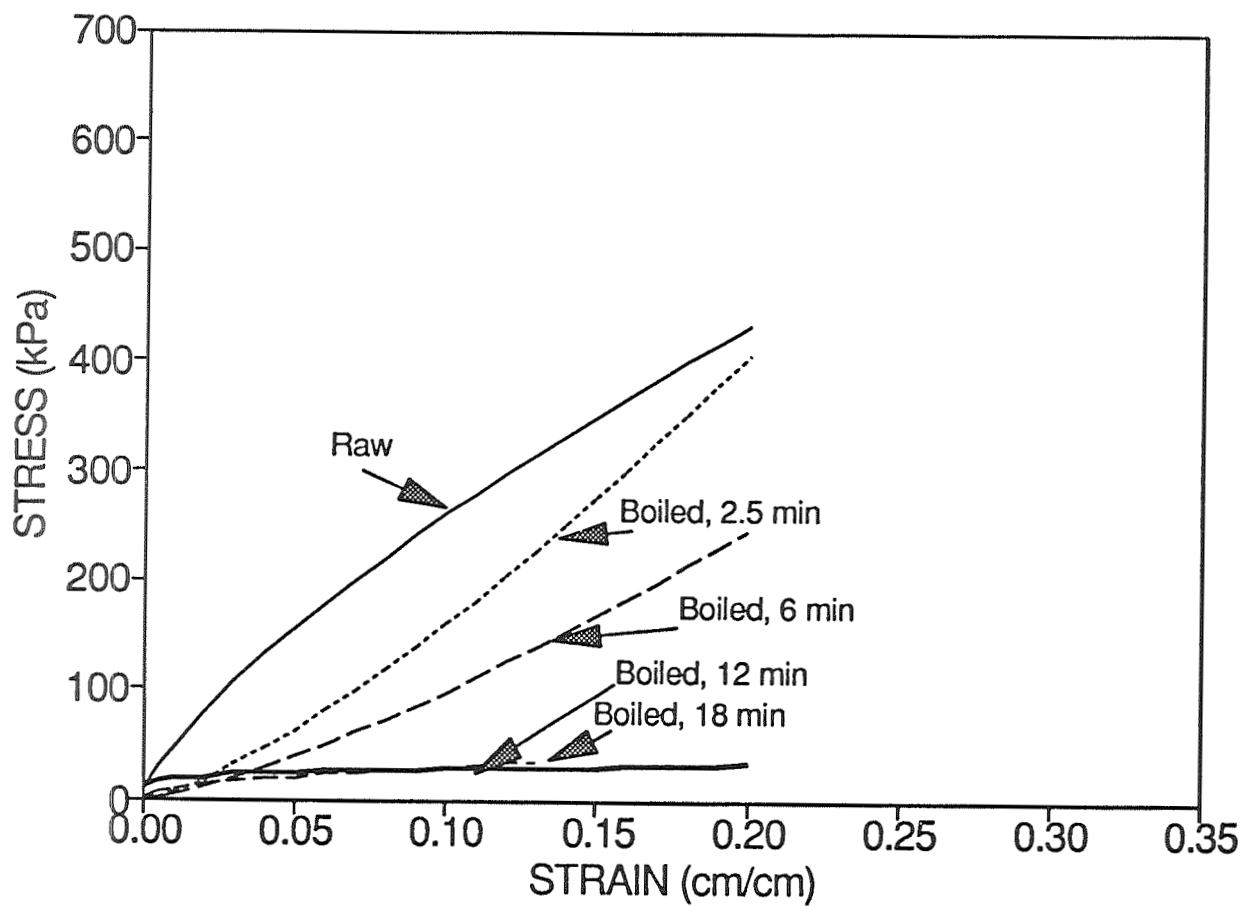


Figure B2: Stress-strain curves for boiled potatoes.

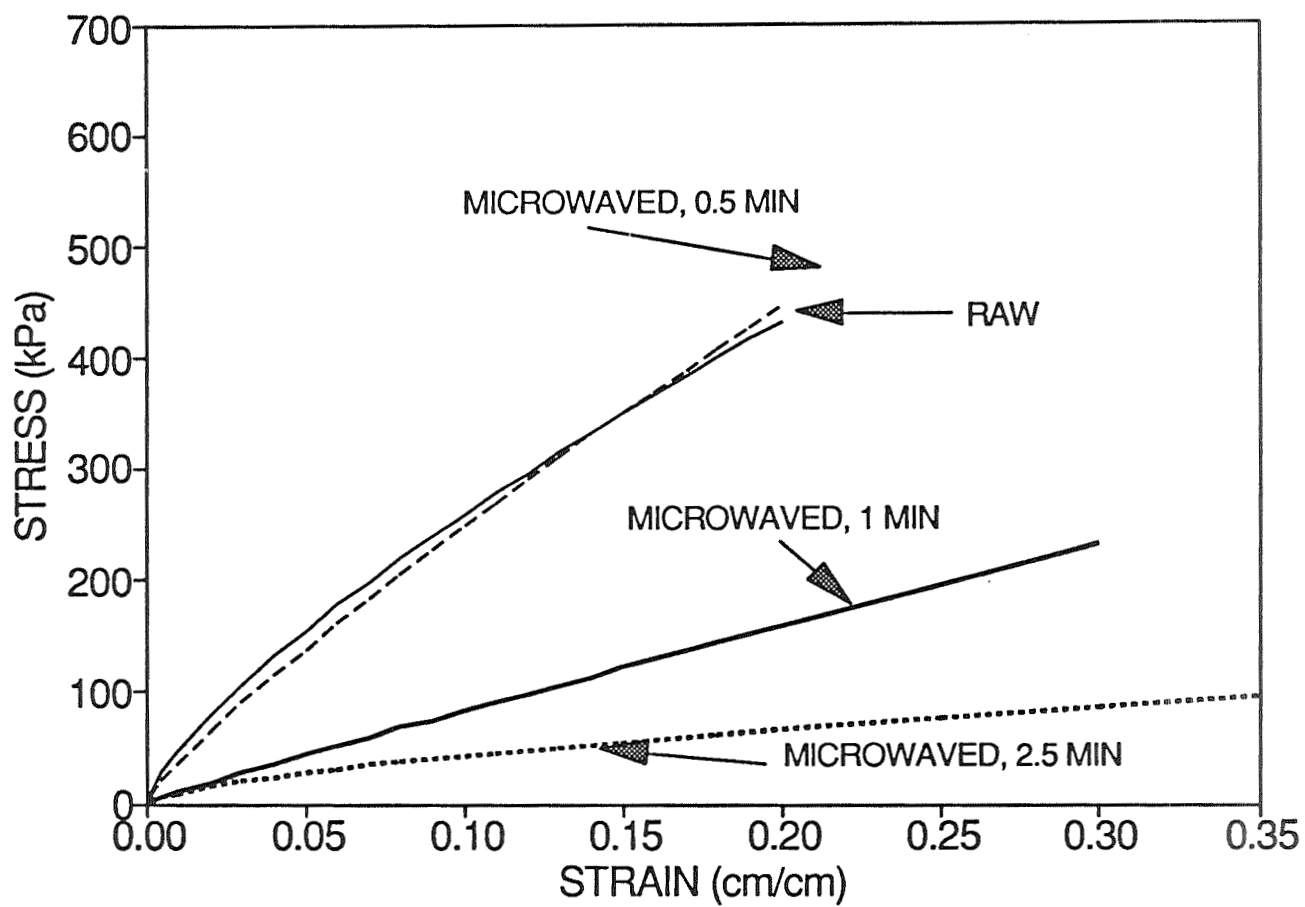


Figure B3: Stress-strain curves for microwaved potatoes.

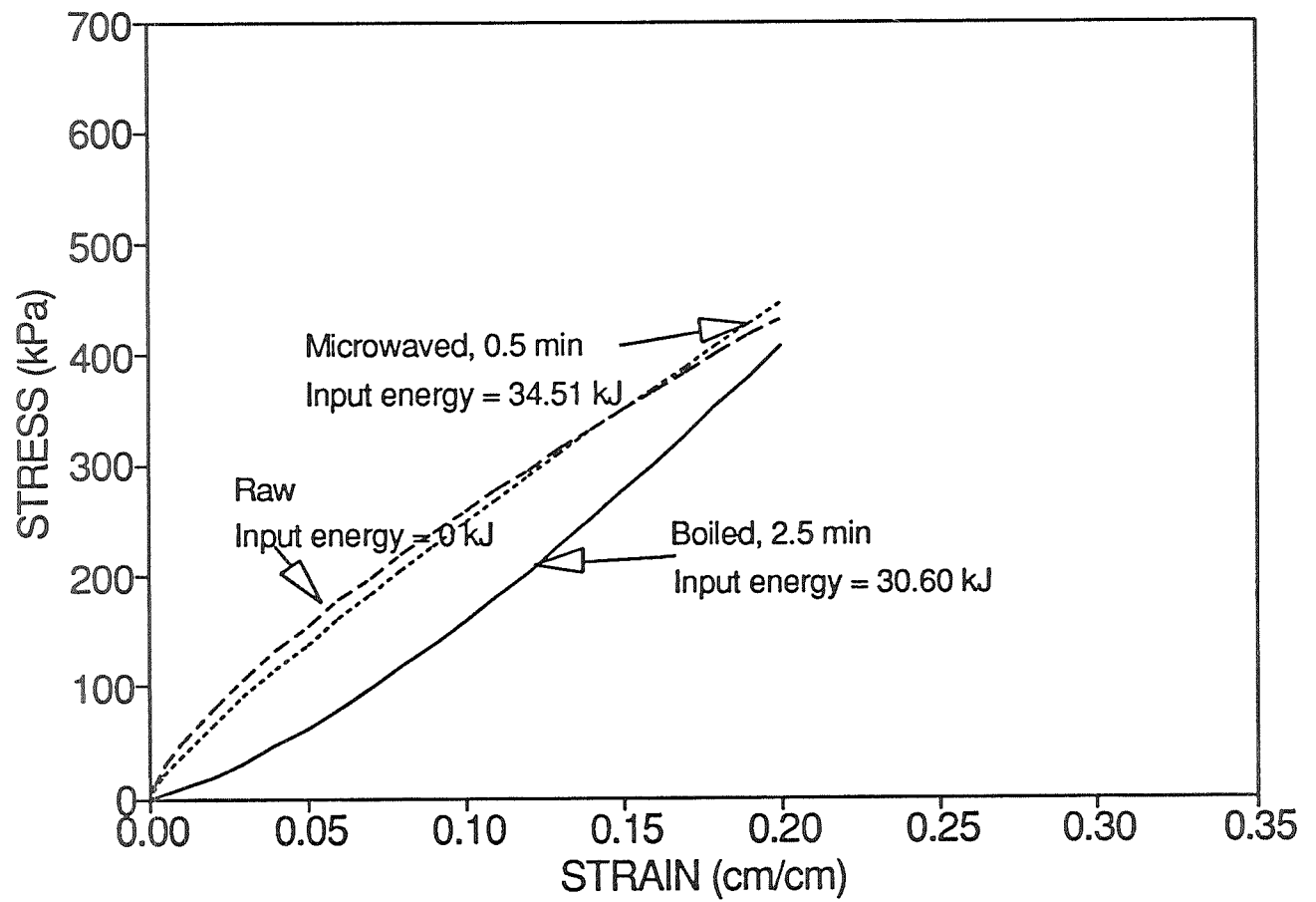


Figure B4: Stress-strain curves for potatoes cooked with input energies between 0 kJ and 40 kJ.

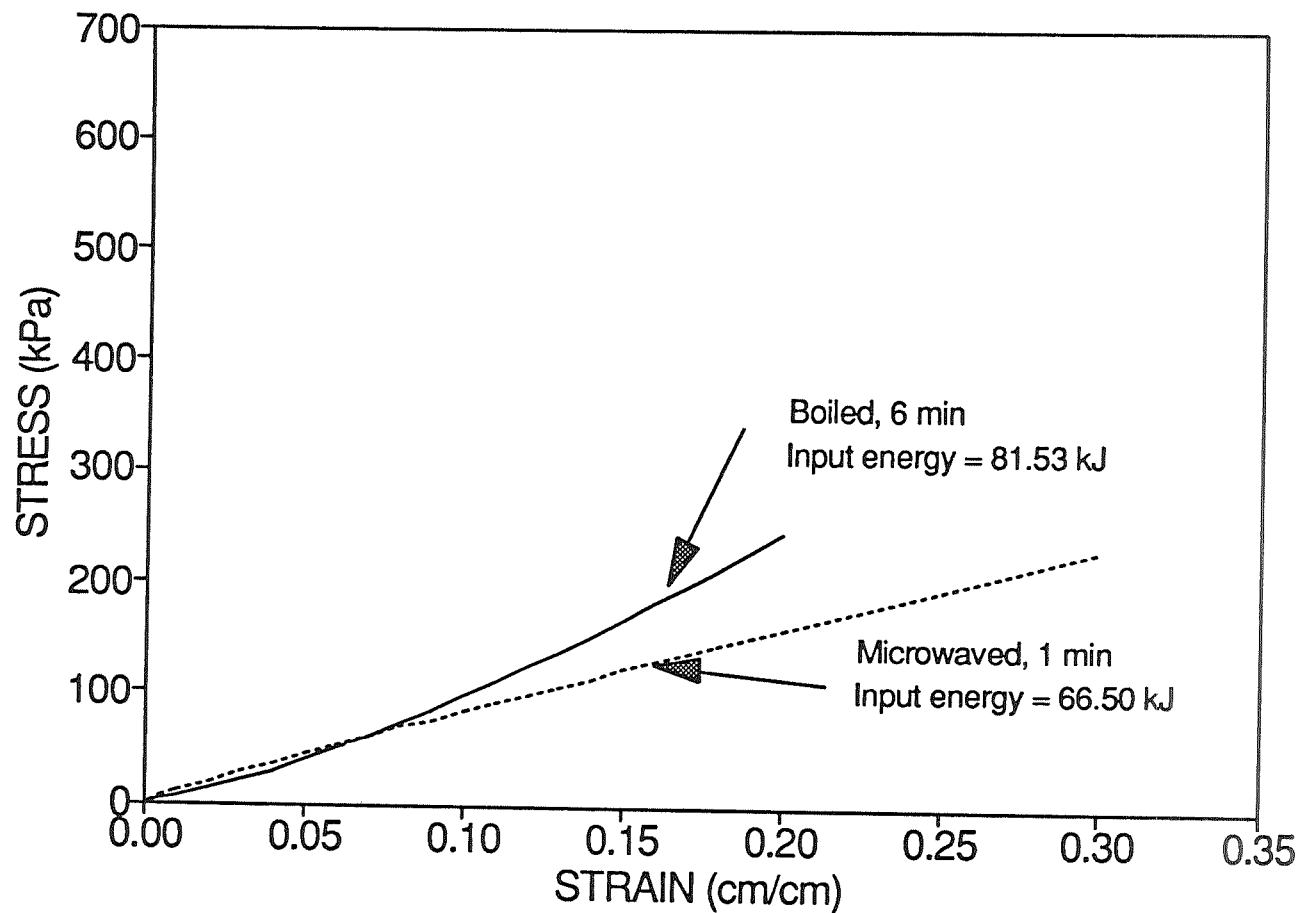


Figure B5: Stress-strain curves for potatoes cooked with input energies between 40 kJ and 100 kJ.

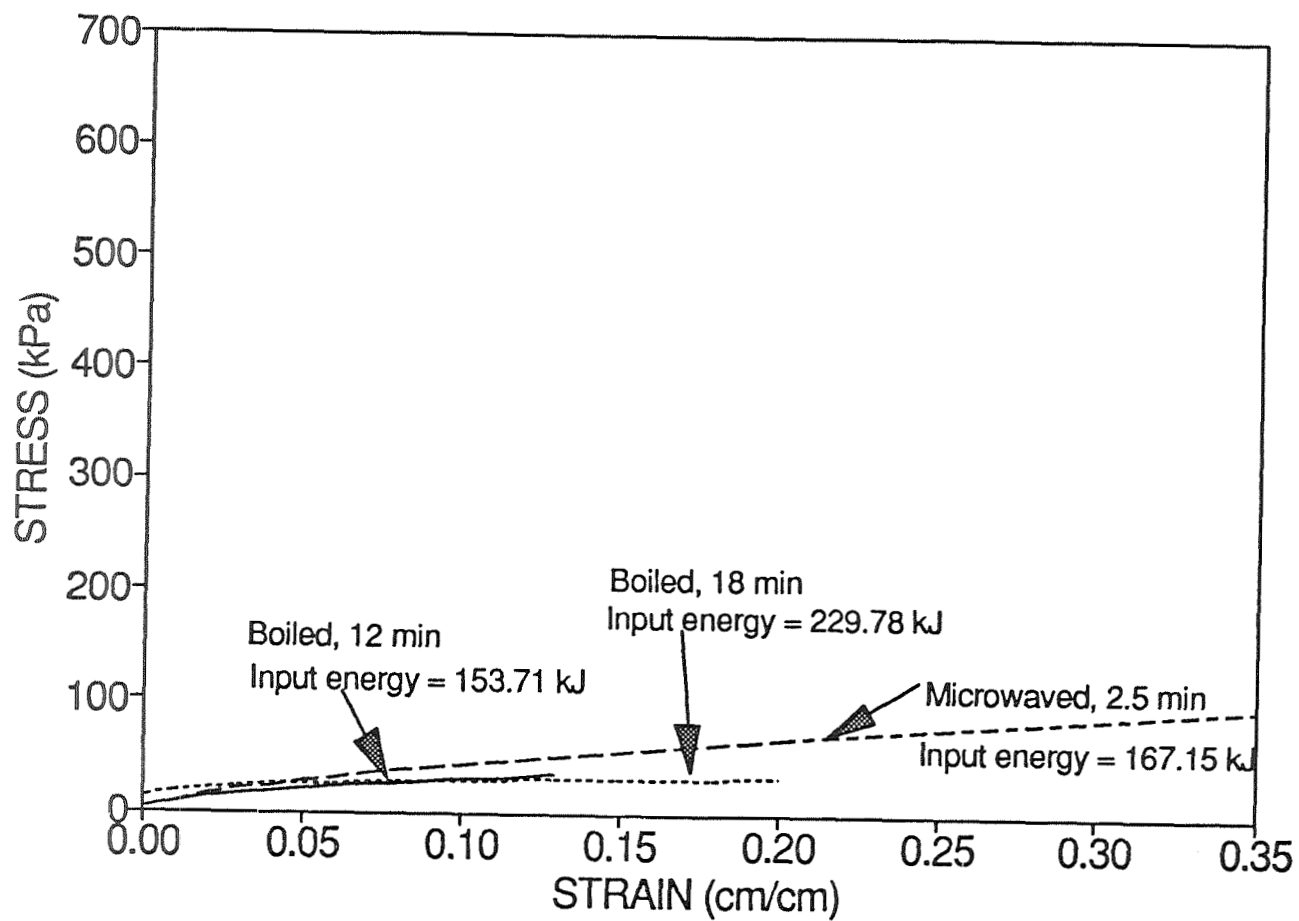


Figure B6: Stress-strain curves for potatoes cooked with input energies over 100 kJ.

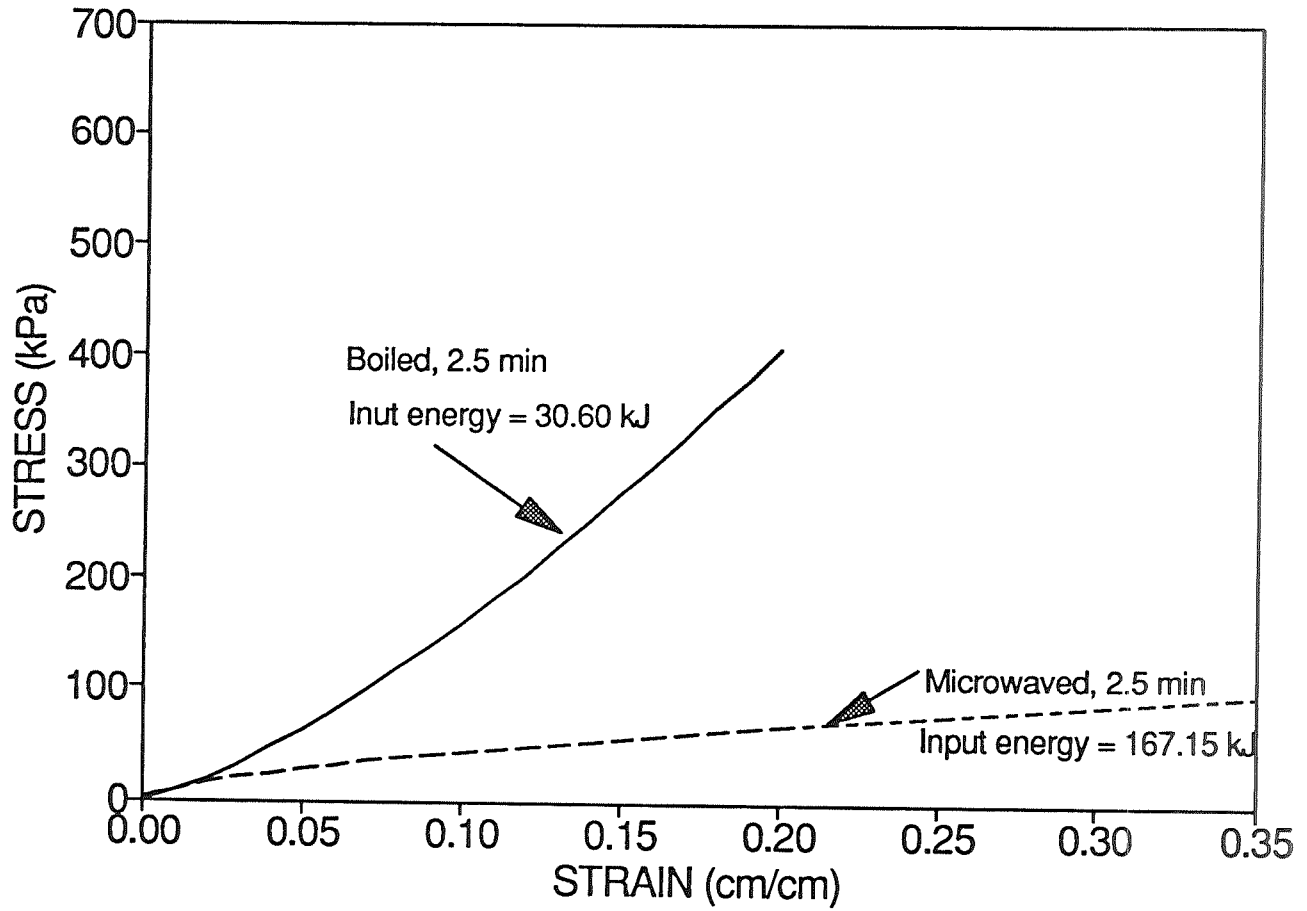


Figure B7: Stress-strain curves for potatoes cooked for 2.5 minutes by different methods.